Successful Implementation of an Alternative Co-located Transfer Standard Audit Approach:

Continuous Deployment of CTS Wind Sensors on a Tall Tower

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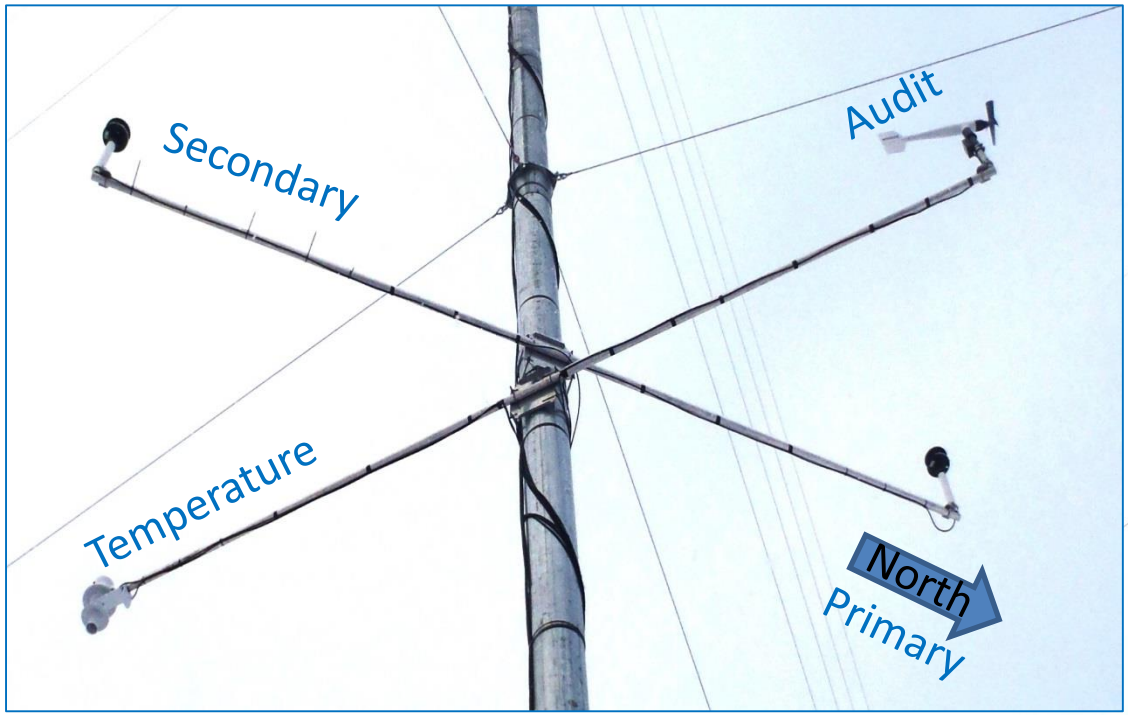
- Teck American, for permission to use their met data
- Mistaya Engineering, Inc., for developing windographer software; www.windographer.com

Measurement Parameters

Measured Parameter	Elevation	Instrument
data loggers (3)	Tower mounted enclosure	Campbell Scientific Inc. (CSI) CR3000, 2-each CR 1000
Air temperature, Relative humidity (dew point)	2-meters (RH) 2,10,20, 50-meters (temp)	CSI CS-215
Barometric pressure	Tower mounted enclosure	CSI CS106, Vaisala PTB110
Motor aspirated temperature and ΔT	2, 10, 20, 50-meters	RM Young 43347 RTD
Precipitation	Ground (off tower location)	CSI CS 700H
Solar radiation	2-meters (separate mast)	Kipp and Zonen CNR4
Sonic ranging snow depth (hydrology only)	2-meters	SR50A
Wind speed and direction	10, 20, 50-meters	Gill WindSonic4-two at each level
Wind speed and direction (hydrology only)	2-meters	Gill WindSonic4
Wind speed and direction (CTS)	**10, 20, 50-meters**	**RM Young Model 05305 AQ**

Tower Configuration



10 meter close-up

CTS Audit Period Selection Approach

- Avoid excessive bias
- Assure that there was a high degree of valid data to audit
- Audit data period selected for every sampling quarter
- Track sensor wear

Audit period selection:

- Select Data from first month of operations
- Choose a week that had close to 100% valid data
- Periods where hourly wind directions were from at least three of four quadrants.
- Finally, select period where all three measurement heights; 10, 20 and 50 meter met the audit qualification simultaneously.

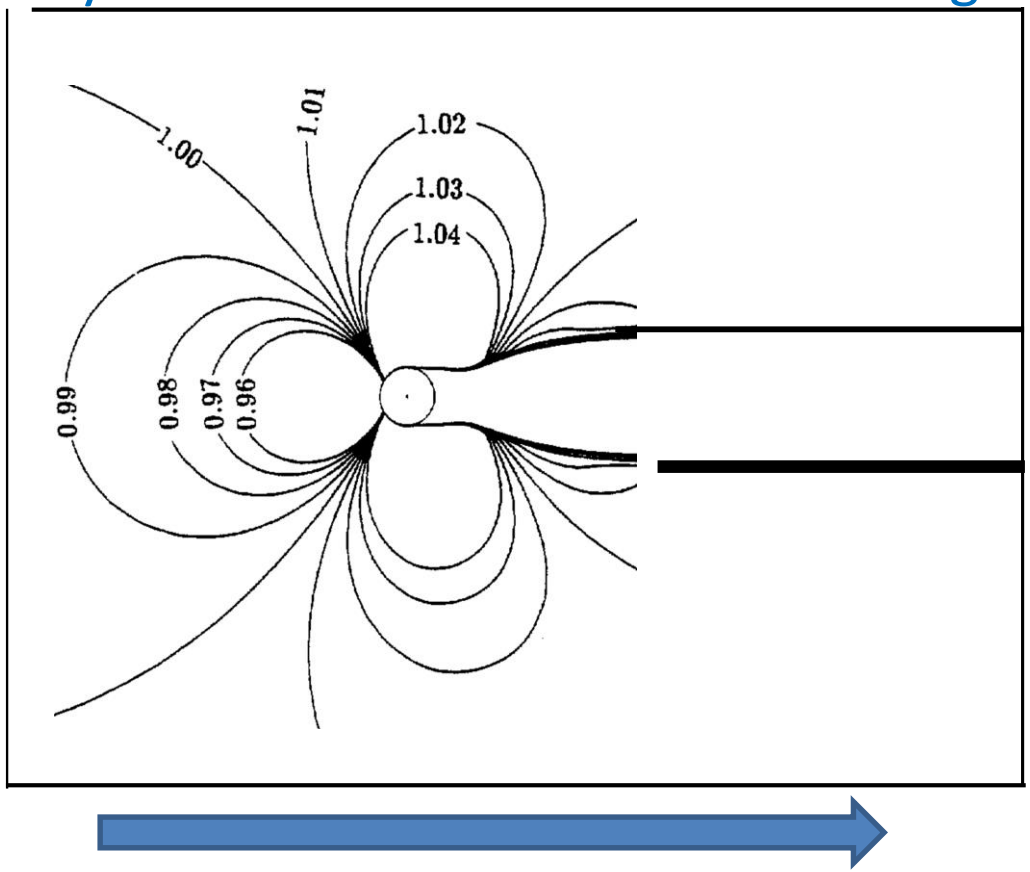
EPA Proposed audit criteria for sonic wind sensors systems*

Wind Variable	Average Difference	Standard Deviation of the Differences	Qualifications
Speed	±0.25 m/s <5 m/s or ±5% **or *<2.5 m/s* above 5 m/s**	0.2 m/s	Wind speeds greater than 1 m/s
Direction	±5°	2°	Wind speeds greater than 1 m/s

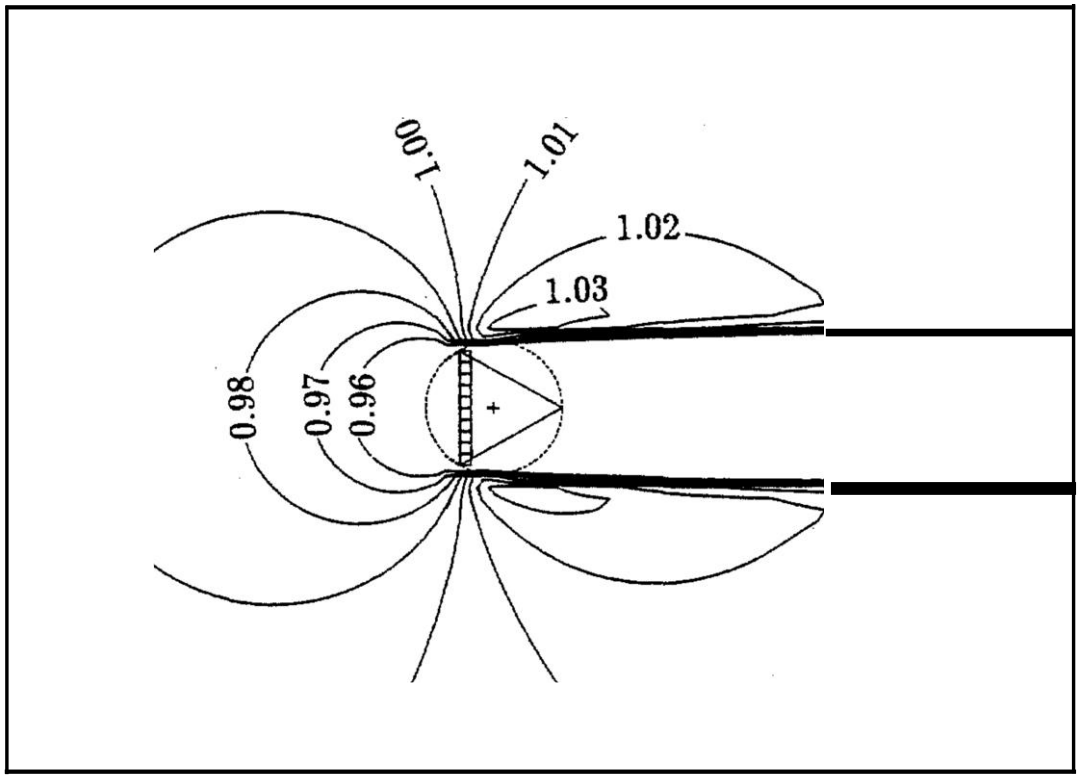
* **Quality Assurance Handbook for Air Pollution Measurement Systems, Table 2-2**
Volume IV: Meteorological Measurements Version 2.0 (Final); *EPA-454/B-08-002* , March 2008

Tower Wake Effects

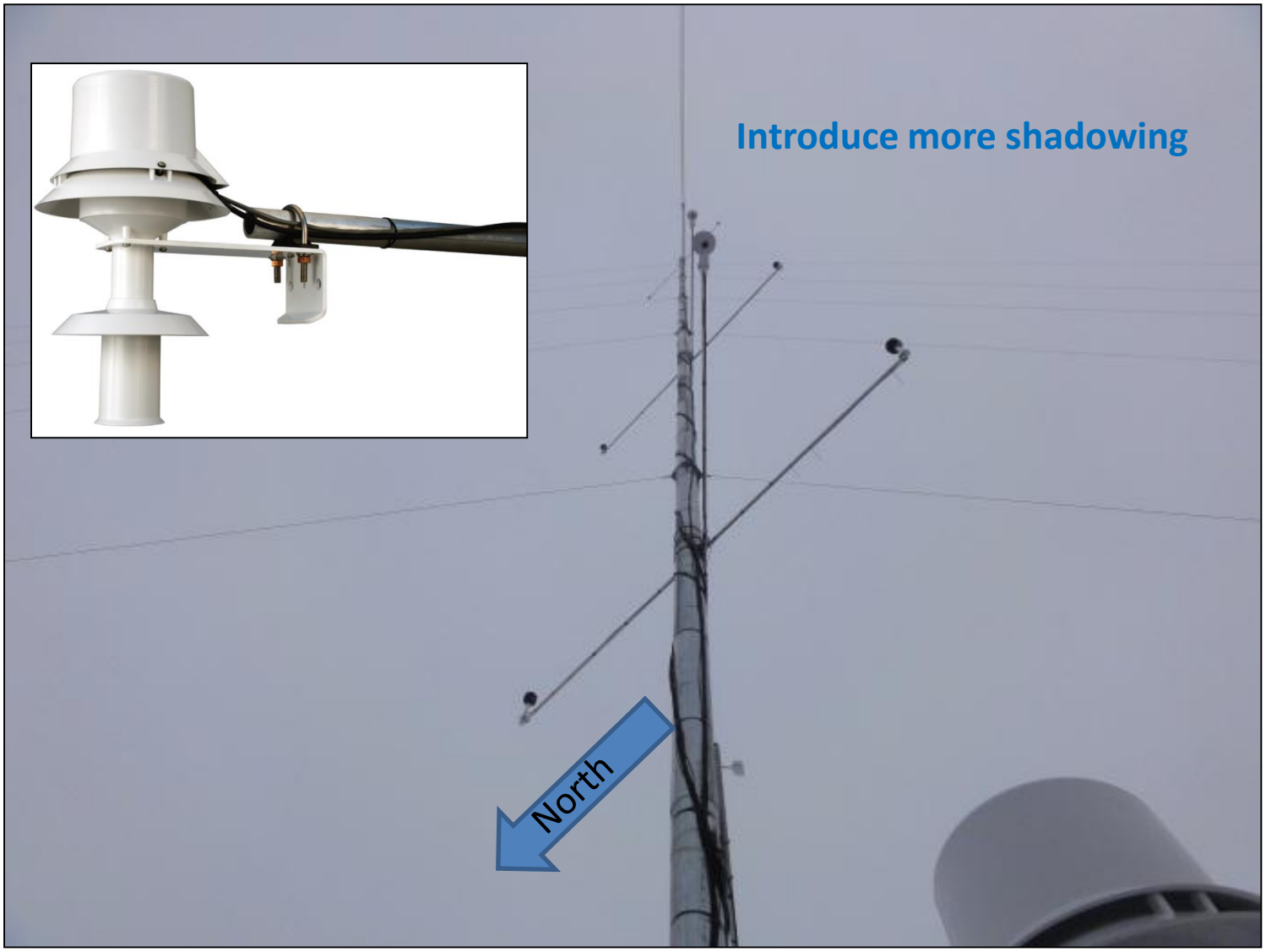
- caused by the tower and instrument mounting booms
- can result in downwind turbulence causing underspeeding of wind speed, and wind direction variability
- Is mitigated by boom orientation and boom length



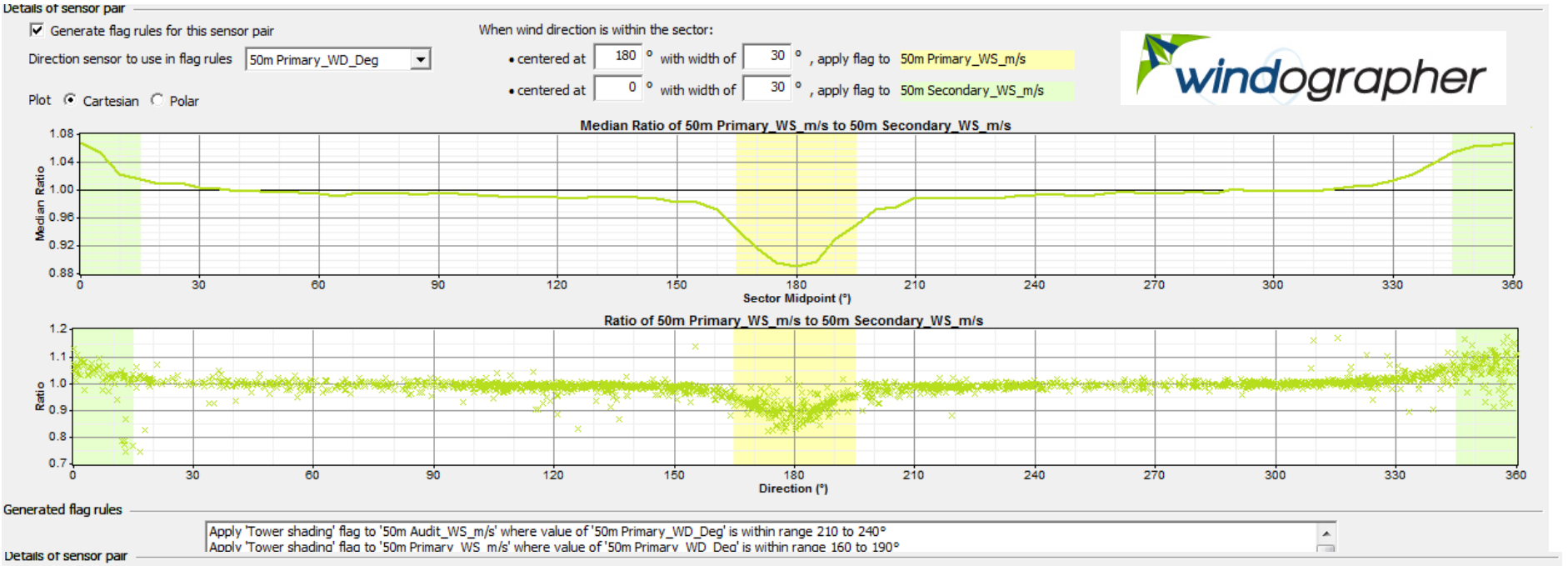
Wakes From Triangular Towers



Temperature sensors & aspirators

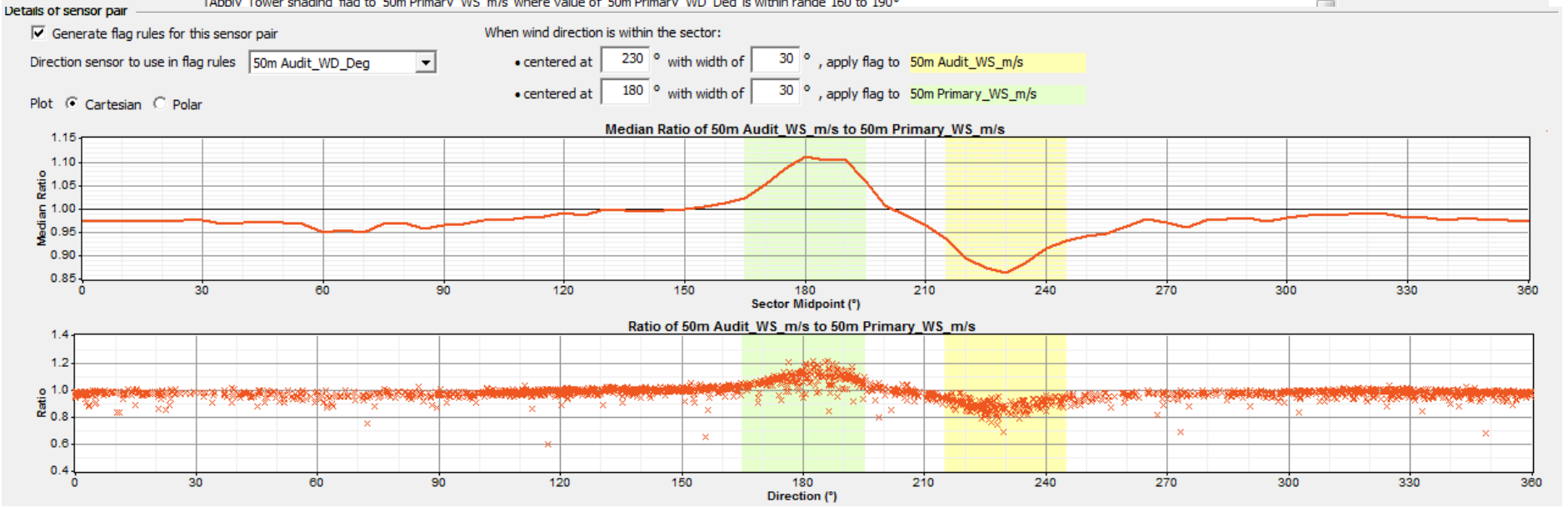


How to remove tower effects?



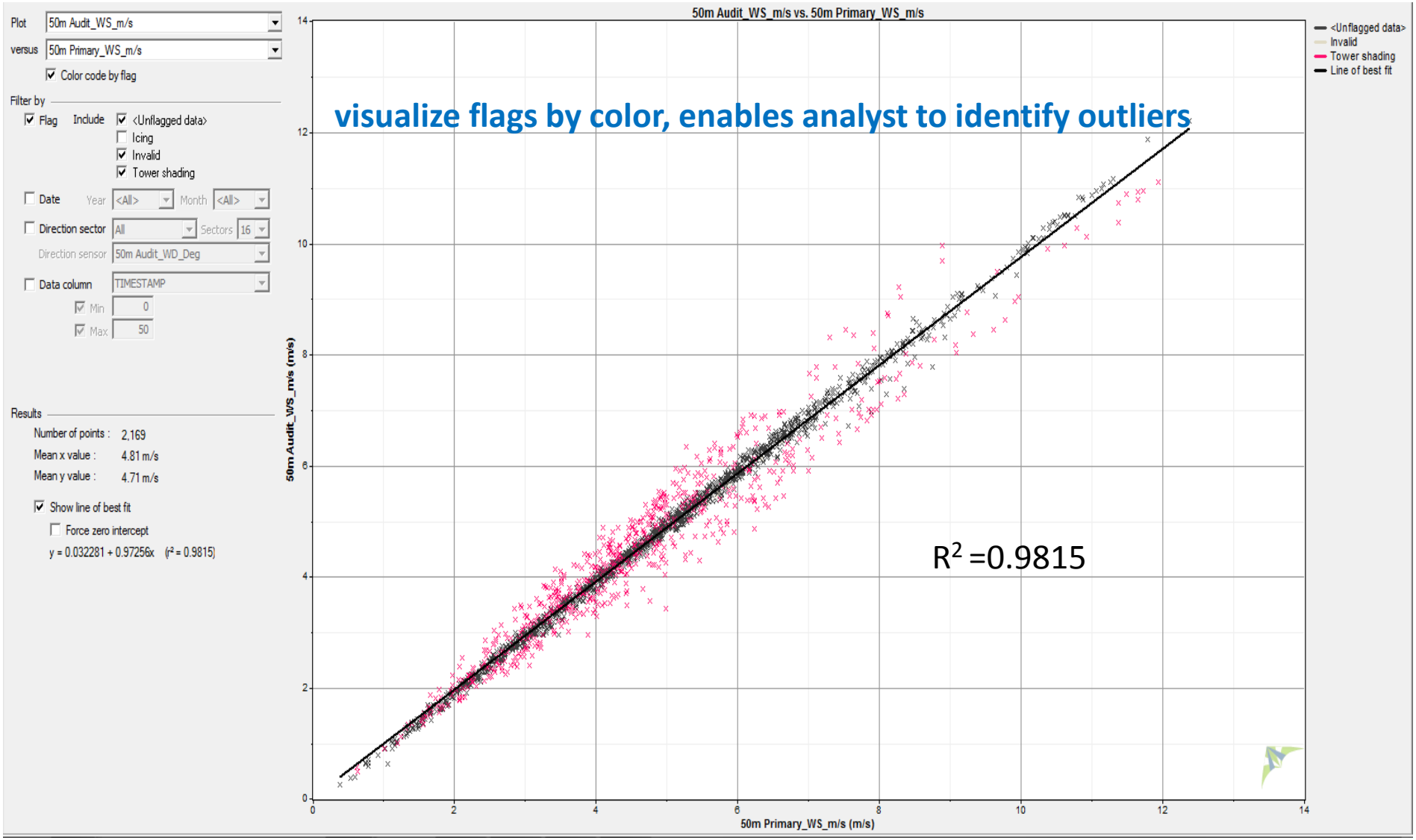
Generated flag rules

Apply 'Tower shading' flag to '50m Audit_WS_m/s' where value of '50m Primary_WD_Deg' is within range 210 to 240°
Apply 'Tower shading' flag to '50m Primary_WS_m/s' where value of '50m Primary_WD_Deg' is within range 160 to 190°



Windographer.com

Scatter plots



Scatter plots-continued

EPA Proposed audit criteria for sonic wind sensors systems*

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* **Quality Assurance Handbook for Air Pollution Measurement Systems, Table 2-2**
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Audit Results

2nd Quarter							Audit Results				
Raw Audit Data, prior 24 hour period											
Height	50 meters										
Sensor	Audit Wind Speed	Audit Wind Direction	Primary Wind Speed	Primary Wind Direction	Secondary Wind Speed	Secondary Wind Direction		P vs A ws	P vs A wd	S vs A ws	S vs A wd
Date								Diff	Diff	Diff	Diff
6/17/2014 15:00	3.763	359.9	3.804	354.4	3.642	357		0.041	-5.5	-0.121	-2.9
6/17/2014 16:00	4.183	15.13	4.203	10.16	4.07	12.91		0.02	-4.97	-0.113	-2.22
6/17/2014 17:00	4.216	24.12	4.238	19.29	4.199	21.94		0.022	-4.83	-0.017	-2.18
6/17/2014 18:00	4.256	24.92	4.251	19.89	4.24	22.5		-0.005	-5.03	-0.016	-2.42
6/17/2014 19:00	3.797	39.32	3.795	34.55	3.818	36.7		-0.002	-4.77	0.021	-2.62
6/17/2014 20:00	4.554	45.54	4.586	40.87	4.591	42.71		0.032	-4.67	0.037	-2.83
6/17/2014 21:00	4.906	45.71	4.96	41.01	4.952	43.07		0.054	-4.7	0.046	-2.64
6/17/2014 22:00	5.088	50.11	5.201	44.62	5.208	46.65		0.113	-5.49	0.12	-3.46
6/17/2014 23:00	5.186	49.26	5.239	43.93	5.246	45.91		0.053	-5.33	0.06	-3.35
6/18/2014 0:00	4.775	84	4.856	77.55	4.879	79.34		0.081	-6.45	0.104	-4.66
6/18/2014 1:00	3.789	106.9	3.884	101.2	3.89	102.6		0.095	-5.7	0.101	-4.3
6/18/2014 2:00	4.268	113.2	4.344	108	4.366	109.8		0.076	-5.2	0.098	-3.4
6/18/2014 3:00	4.384	99.1	4.49	93.1	4.46	94.8		0.106	-6	0.076	-4.3
6/18/2014 4:00	4.462	83.4	4.58	76.46	4.575	78.12		0.118	-6.94	0.113	-5.28
6/18/2014 5:00	4.373	89.8	4.469	83.5	4.506	85.2		0.096	-6.3	0.133	-4.6
6/18/2014 6:00	5.788	110.9	5.822	105.7	5.812	107.4		0.034	-5.2	0.024	-3.5
6/18/2014 7:00	6.726	121.9	6.662	117	6.718	118.8		-0.064	-4.9	-0.008	-3.1
6/18/2014 8:00	6.544	121.5	6.49	116.5	6.593	118.4		-0.054	-5	0.049	-3.1
6/18/2014 9:00	6.363	106.4	6.406	100.8	6.412	102.5		0.043	-5.6	0.049	-3.9
6/18/2014 10:00	5.609	111.5	5.612	106.2	5.668	107.7		0.003	-5.3	0.059	-3.8
6/18/2014 11:00	5.611	106.1	5.653	100.4	5.656	102.2		0.042	-5.7	0.045	-3.9
6/18/2014 12:00	6.273	127.7	6.205	122.9	6.287	124.5		-0.068	-4.8	0.014	-3.2
6/18/2014 13:00	6.617	126.9	6.541	121.7	6.648	123.5		-0.076	-5.2	0.031	-3.4
6/18/2014 14:00	6.857	114.5	6.847	109.1	6.92	111.2		-0.01	-5.4	0.063	-3.3
							Criteria	±0.25 m/s or ±5%/0.2	±5°/2°	±0.25 m/s or ±5%/0.2	±5°/2°
							Avg.	0.61	-5.37	0.79	-3.43
							Sdev	0.06	0.57	0.06	0.78

Audit Results - continued

- 6 quarterly ‘snapshot’ 24-hr audits conducted to date
  - Winter audits had more outliers due to icing events and different prevailing wind directions causing more shadowing
  - No indication of bearing degradation since audit results remain consistent
  - Valuable to identify vane offset on 50m

Audit Results – continued
50 meters

Sensor				50 meter Primary						50 meter Secondary					
Quarter		EPA Proposed Audit Criteria		1st Qtr 2013	2nd Qtr 2013	3rd Qtr 2013	4th Qtr 2013	1st Qtr 2014	2nd Qtr 2014	1st Qtr 2013	2nd Qtr 2013	3rd Qtr 2013	4th Qtr 2013	1st Qtr 2014	2nd Qtr 2014
Wind Speed	Average Difference	±0.25 m/s <5 m/s	Or 5% >5 m/s	0.14 m/s	0.11 m/s	3%	0.22 m/s	0.17 m/s	0.61%	**0.27 m/s**	0.13 m/s	3%	0.24 m/s	0.21 m/s	0.79%
	Standard Deviation of the Differences	0.2 m/s		0.2	0.1	0.3	0.0	0.1	0.1	0.2	0.1	0.3	0.0	0.1	0.1
Wind Direction	Average Difference	±5°		**-6**	**-6**	**-6**	**-5**	**-6**	**-5**	-3	-3	-2	-3	3	-3
	Standard Deviation of the Differences	2°		1	1	1	1	1	1	2	1	0	2	1	1

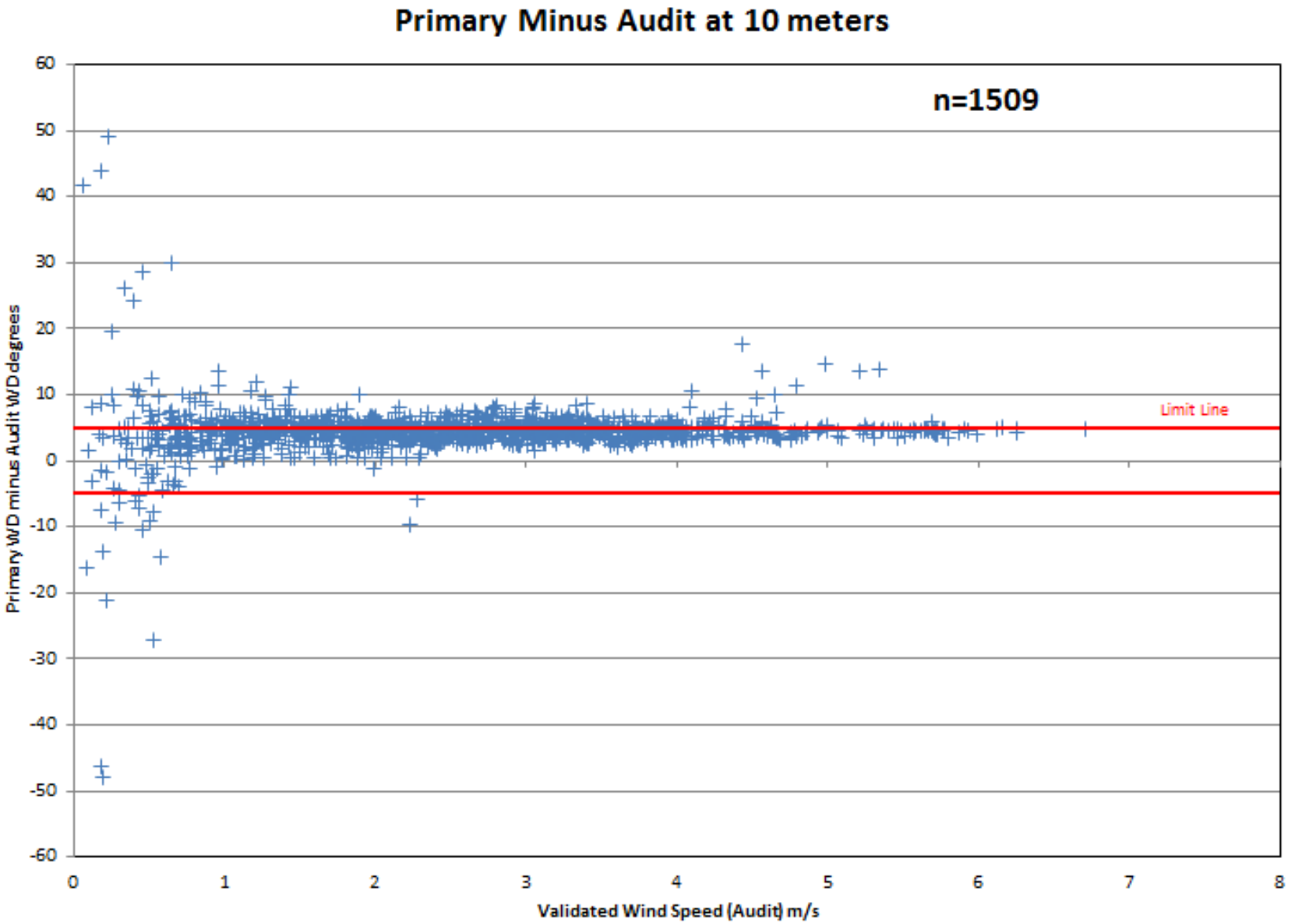
Audit Results – continued
20 meters

Sensor		20 meter Primary						20 meter Secondary					
Quarter		1st Qtr 2013	2nd Qtr 2013	3rd Qtr 2013	4th Qtr 2013	1st Qtr 2014	2nd Qtr 2014	1st Qtr 2013	2nd Qtr 2013	3rd Qtr 2013	4th Qtr 2013	1st Qtr 2014	2nd Qtr 2014
Wind Speed	Average Difference	0.21 m/s	0.12 m/s	0.20 m/s	0.25 m/s	0.15 m/s	0.14 m/s	0.25 m/s	0.15 m/s	0.19 m/s	0.20 m/s	0.18 m/s	0.12 m/s
	Standard Deviation of the Differences	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1
Wind Direction	Average Difference	-1	-1	0	0	-0.5	-1	-2	-2	0	-2	-2	-3
	Standard Deviation of the Differences	2	2	1	1	3	1	2	2	1	2	3	1

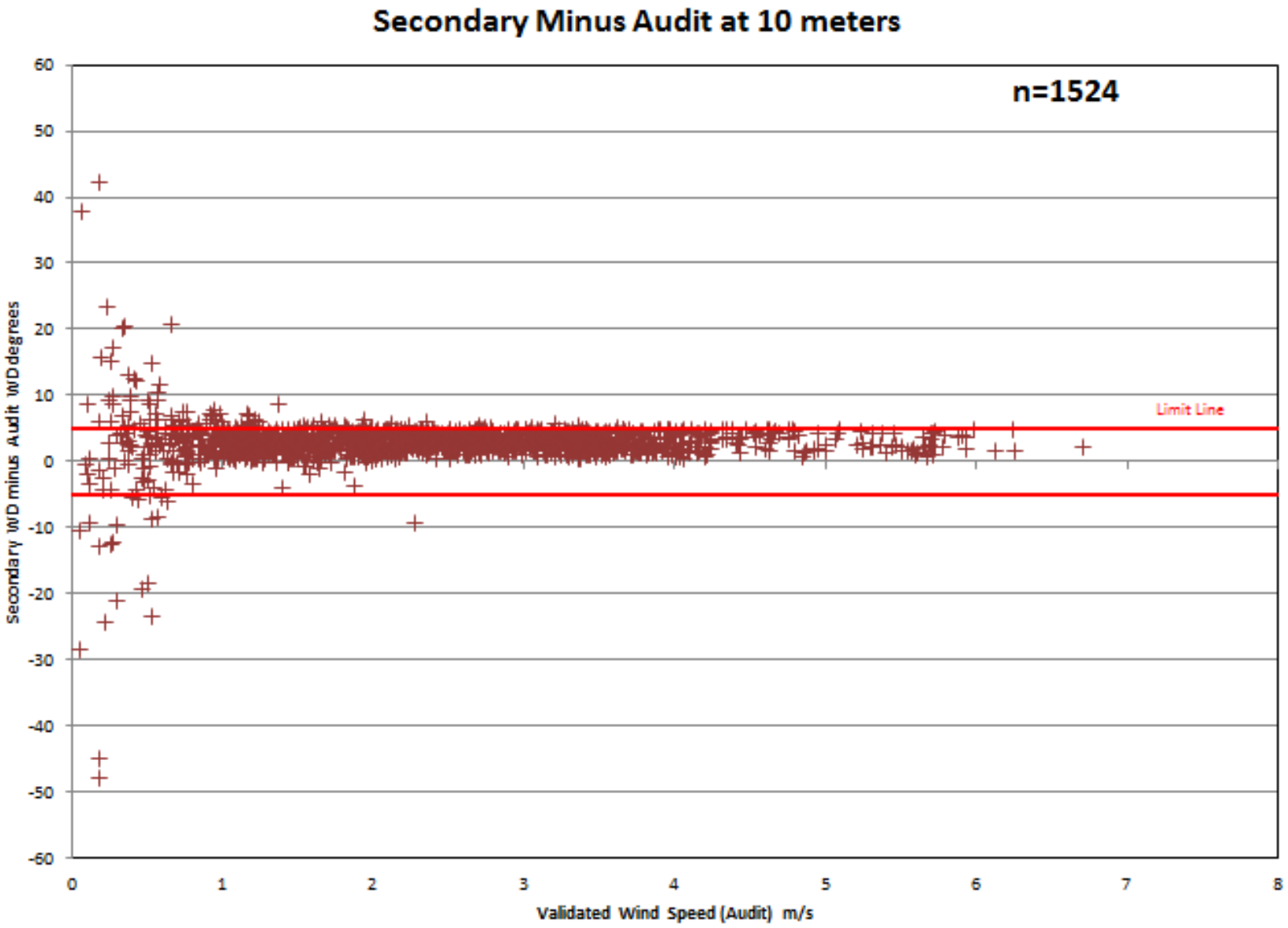
Audit Results – continued
10 meters

Sensor		10 meter Primary						10 meter Secondary					
Quarter		1st Qtr 2013	2nd Qtr 2013	3rd Qtr 2013	4th Qtr 2013	1st Qtr 2014	2nd Qtr 2014	1st Qtr 2013	2nd Qtr 2013	3rd Qtr 2013	4th Qtr 2013	1st Qtr 2014	2nd Qtr 2014
Wind Speed	Average Difference	0.17 m/s	0.11 m/s	0.20 m/s	0.20 m/s	0.16 m/s	0.16 m/s	0.09 m/s	0.14 m/s	0.15 m/s	0.23 m/s	0.15 m/s	0.12 m/s
	Standard Deviation of the Differences	0	0	0.1	0	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1
Wind Direction	Average Difference	5	5	5	5	3	5	3	3	4	4	4	2
	Standard Deviation of the Differences	2	1	1	2	2	1	1	2	1	1	2	1

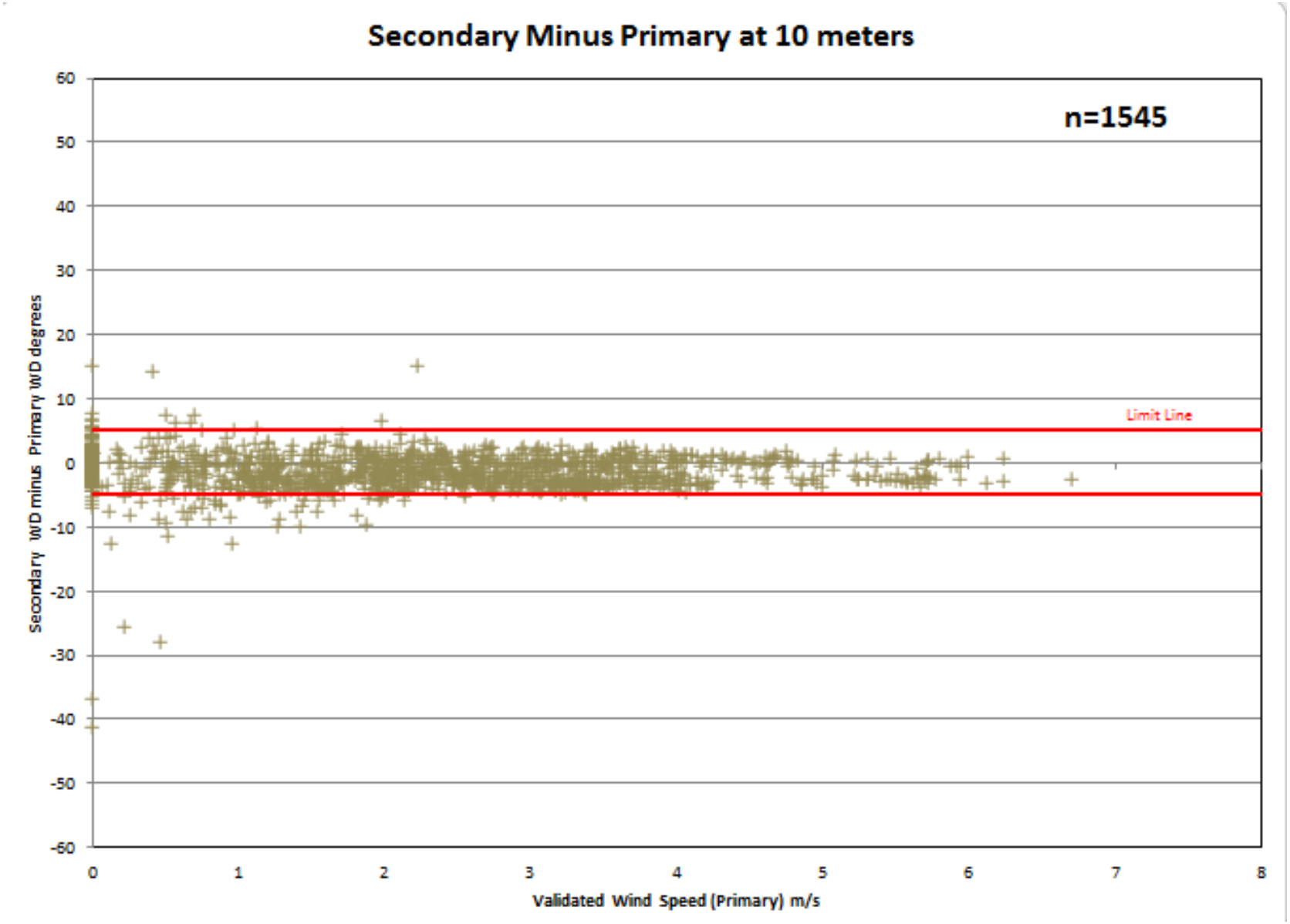
Hourly data for Quarter compared to audit criteria



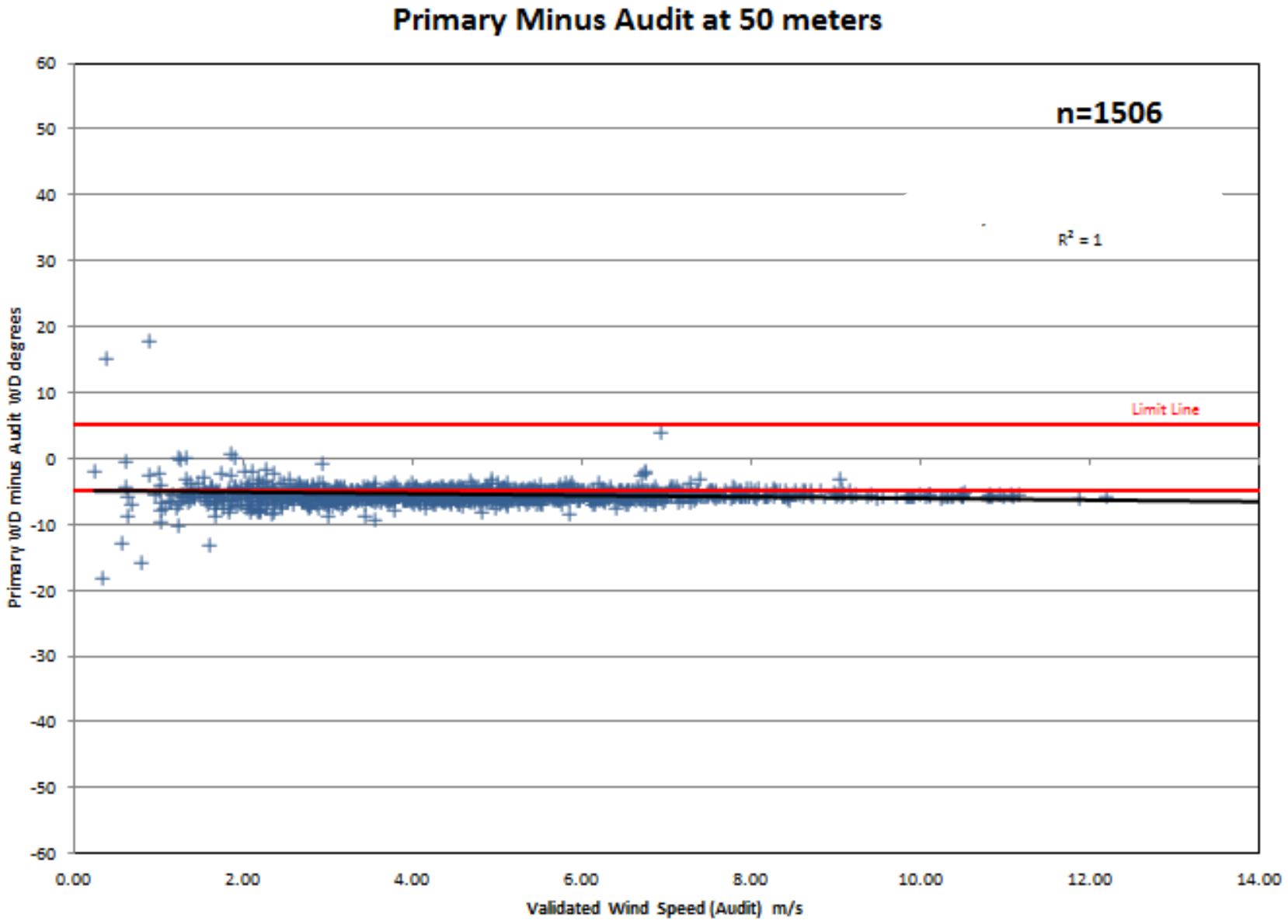
Hourly data for Quarter compared to audit criteria



Hourly data for Quarter compared to audit criteria



Hourly data for Quarter compared to audit criteria



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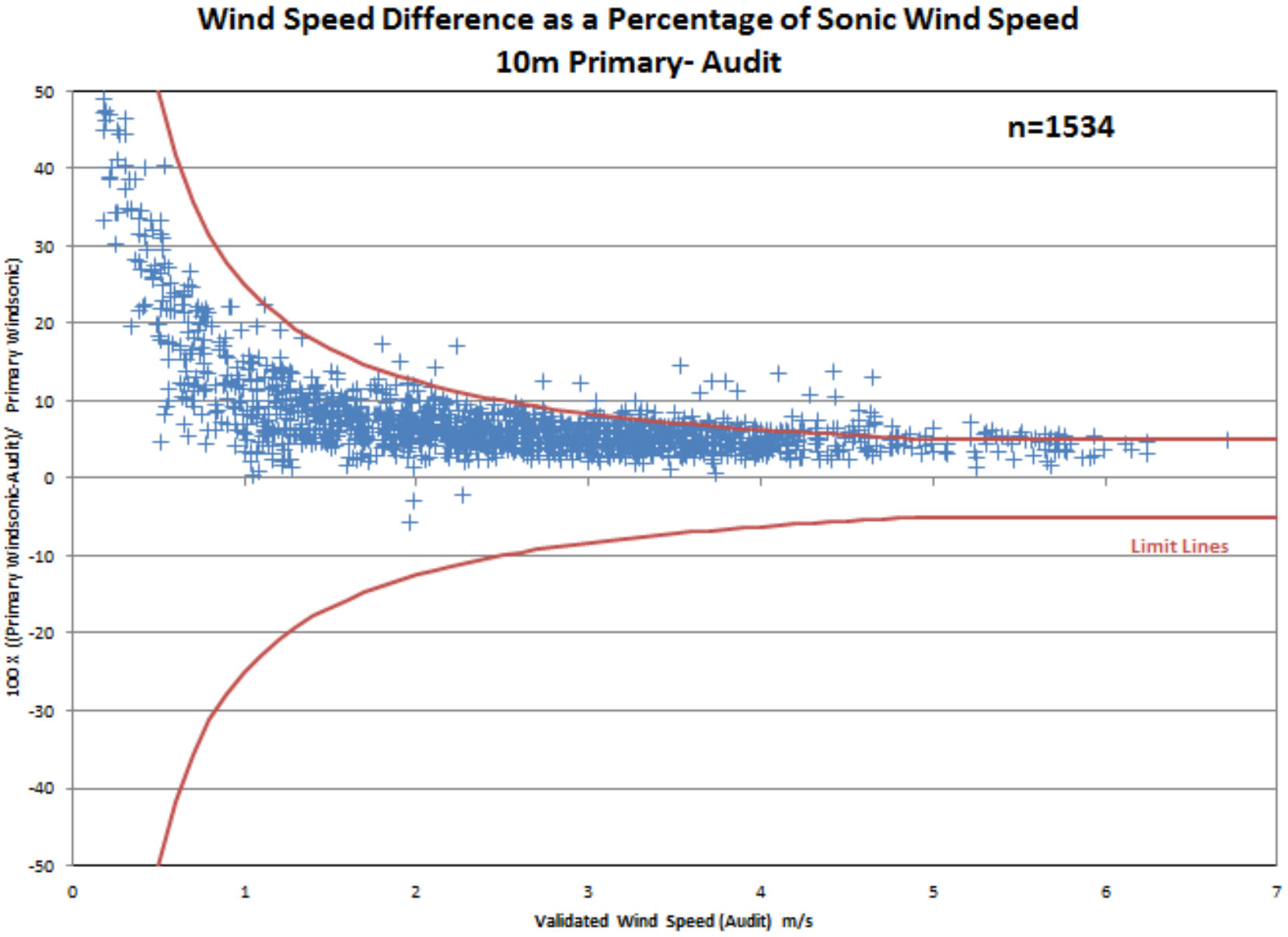

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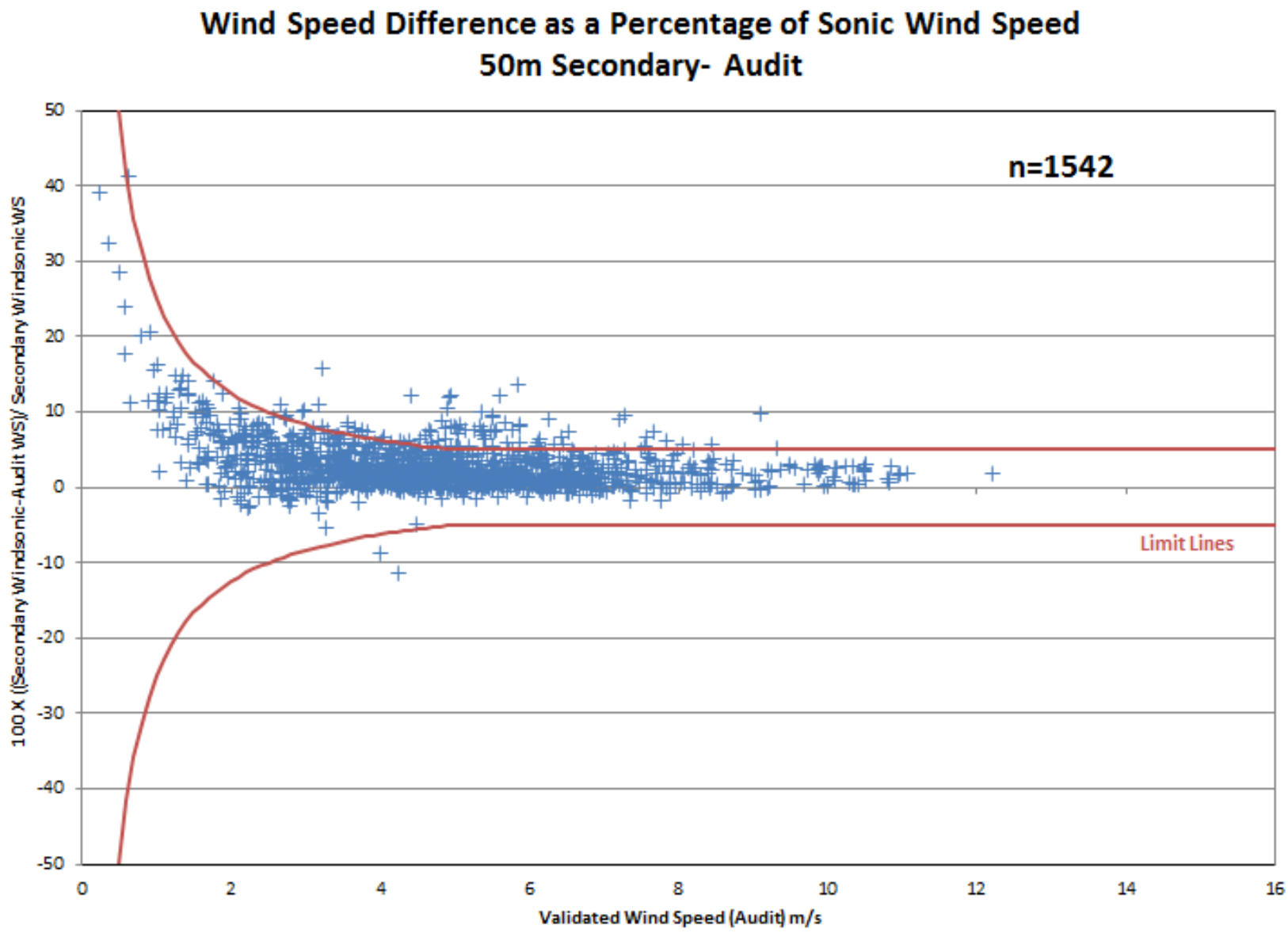

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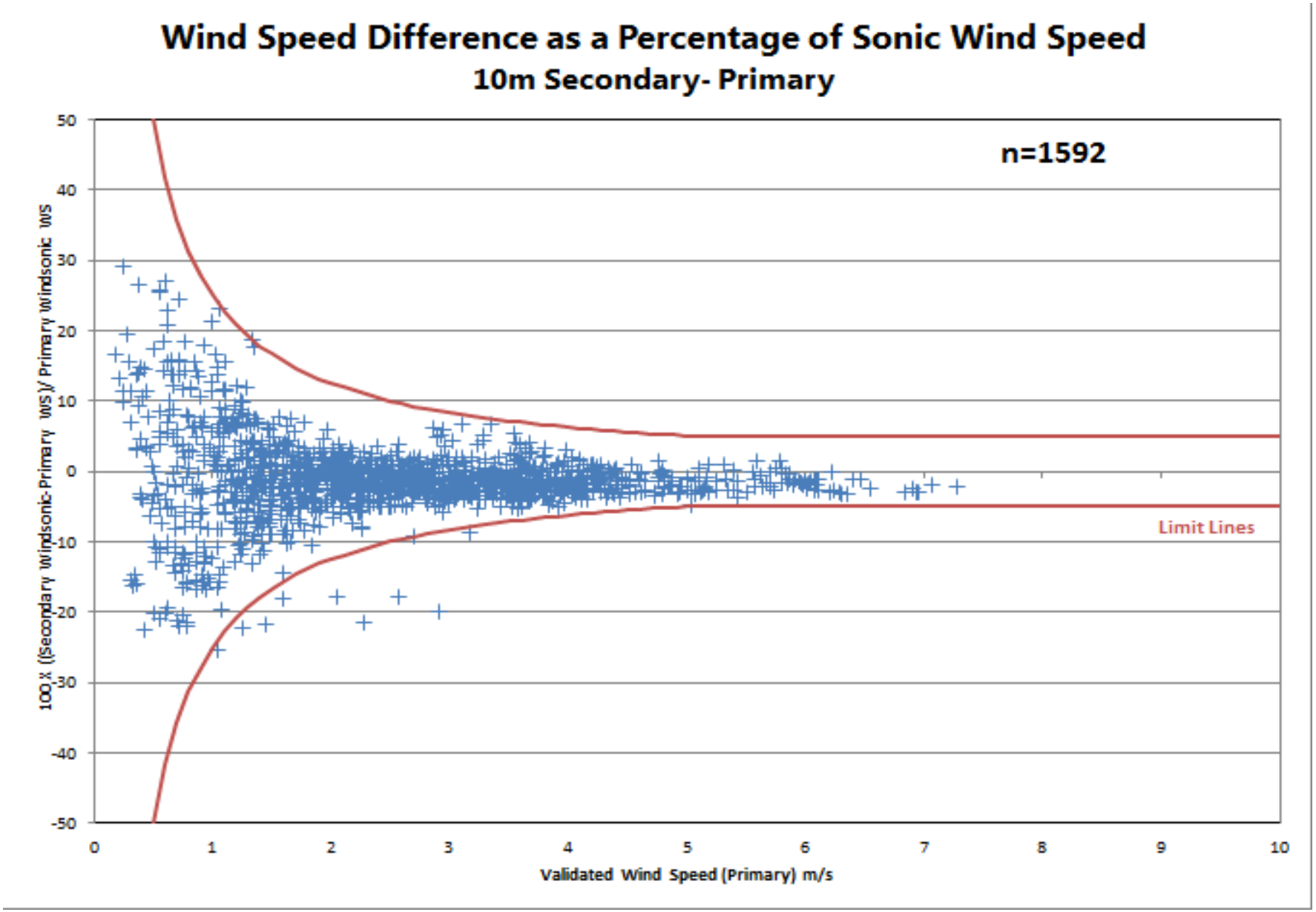

Data recovery for 2nd Quarter 2014

Data recovery after Shadow & Outlier removal	
Sensor	2nd Quarter 2014
50-meter primary wind speed & direction	81.9%
50-meter secondary wind speed & direction	82.0%
50-meter audit wind speed & direction	87.0%
20-meter primary wind speed & direction	83.8%
20-meter secondary wind speed & direction	85.2%
20-meter audit wind speed & direction	84.1%
10-meter primary wind speed & direction	85.4%
10-meter secondary wind speed & direction	85.8%
10-meter audit wind speed & direction	83.7%

Percent of data meeting audit criteria after shadow and outlier removal

Sensor		2nd Quarter Percent of Qualified Data passing 24 hour Audit Criteria			
		Wind Speed		Wind Direction	
		Average Difference	Standard Deviation of the Differences	Average Difference	Standard Deviation of the Differences
Criteria		±0.25 m/s < 5m/s or ±5%	0.2 m/s	±5°	2°
50 meters	Primary Minus Audit	95.4%	97.5%	36.0%	95.4%
	Secondary Minus Audit	93.35%	97.67%	98.01%	95.08%
	Secondary Minus Primary	99.89%	99.57%	99.89%	96.79%
20 Meters	Primary Minus Audit	89.8%	96.7%	97.6%	90.1%
	Secondary Minus Audit	89.9%	97.9%	97.2%	88.8%
	Secondary Minus Primary	99.2%	96.3%	100.0%	95.0%
10 Meters	Primary Minus Audit	90.4%	97.7%	82.9%	85.7%
	Secondary Minus Audit	96.1%	97.3%	96.8%	92.3%
	Secondary Minus Primary	100.00%	100.00%	100.00%	89.83%

Ongoing Project Tasks & Additional Studies

- Further utilize Windographer for outlier determination and flagging data
- Build ‘model-input’ database following EPA substitution guidance; three valid wind measurements available at each height.
- Investigate additional time intervals--1-minute, 15-minute
- Automate outlier removal based on speed and/or direction criteria

What might be done differently to improve method?

- More vertical separation on tower between audit/temperature booms and sonics to reduce wake effects
- Be sure to account for prevailing winds-we were successful on this project

Conclusions

- Data show that hourly data successfully meets the proposed audit criteria.
- Biases can be clearly identified, and data can be corrected for model input or compliance uses
- Sonic sensors are in very good agreement
- Quarter-by-quarter audit consistency also demonstrates that the propeller-vane sensor performance is not degrading through 18 months of operation
- After tower shadow identification and flagging, substitution using data from multiple sensors can build model input dataset; i.e. selection based on wind quadrant

Thank you…..questions??

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